INTELLIGENT IMPLEMENTATION OF A MICROCONTROLLER-BASED CLOSED-LOOP PROCESS CONTROL SYSTEM

Adrian Surpăţeanu, Costin Ştefănescu, Nicolae Cupcea

Computer Science Department, Automatic Control and Computers Faculty,
University "POLITEHNICA" of Bucharest
313 Splaiul Independenţei, 60042 Bucharest, Romania
Phone/Fax: +(40) 21-402.93.51
e-mail: adrian.surpateanu@cs.pub.ro, costin.stefanescu@cs.pub.ro, nicolae.cupcea@cs.pub.ro

Abstract: The latest applications in automatic control can be defined as being high intelligent structures, and allowing using new operating and analysis techniques and algorithms for process control. This paper is focused on interdisciplinary, systemic approach of designing a closed-loop temperature control system. Developed using an intelligent hardware, a distributed (oriented at the hardware-layer and a personal computer layer) software application is performing the process identification, adjusting the control parameters and the process control. The system allows the process evolution view and keeping an extended history of its evolution.

Keywords: advanced control, numerical PID controller, microcontroller-based intelligent structure, distributed software application.

1. OVERVIEW

A great importance for assessing quality of glass-made products is represented by obtaining information regarding the dependence viscosity versus temperature, the viscosity being the major property of glass. The metrological control of viscosity as the most important control property during the technological glass production process, into an intermediate state of elaboration, may surprise some abnormal aspects in technological phenomena progress.

In practice, the viscosity as function of temperature is useful for controlling the entire production process, starting from the melting glass from the oven and finishing with special thermal treatments.

The curve illustrating the viscosity dependence versus temperature is obtained by performing large series of measurements in order to determine the viscosity fixed points, as shown in Table 1.

Table 1. Glass Viscosity Fixed Points

$\log_{10}$(viscosity in Pa x s)	Description
1	Melting point (glass melt homogenization and fining)
3	Working point (pressing, blowing)
4	Flow point
6.6	Littleton softening point (glass deforms under its own weight)
8-10	Dilatometric softening point T_d, depending on load
10.5	Deformation point
11-12.3	Glass Transition Temperature T_g
12	Annealing point (stress is relieved within a few minutes)
13.5	Strain point (stress is relieved within several hours)

Each specific temperature is generally determined by using a large amount of specialized apparatus, in a independent way.

The dedicated system described in this paper is an embedded system prototype (multifunctional prototype, developed using measurement and control modules), which eliminates the need to use specific apparatus and dramatically reduces the implementation costs of an industrial laboratory.

The paper describes some original solutions used to develop this prototype organized around a hardware core, which can be described as a low cost and high versatility structure, based on MSC1210 microcontroller from Texas Instruments (fig. 1).

Industrial process control implies to measure the physical parameters of the process and to control them according to an appropriate control strategy.

In the same time as the development of the analytical instruments and the synthesis of the control systems, took place a spectacular evolution of numerical (hardware and software) equipments determining an easy way to implement modern control systems with some certain advantages versus the analogical solutions: the easiness of implementation, flexibility and low cost.

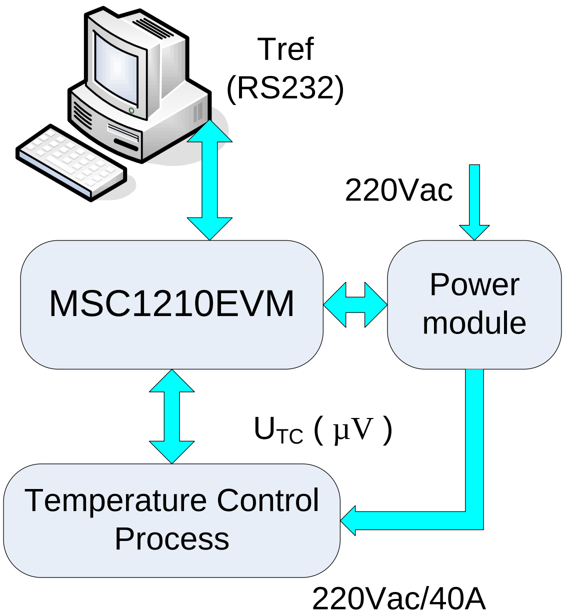

Fig. 1. Block diagram of the control system

The optimal implementation solution is represented by a distributed hardware-software architecture: a microcontroller core which is supervised by a PC computer. According to the high range of temperature variation of the presented process, we have chosen as temperature sensor a B-type thermocouple (Pt-30% Rh, temperature range 0-1820^{o}C). From the system implementation point of view, this restriction determines two different ways of conducting the designing process:

- Using a thermocouple to voltage adaptor and a general purpose microcontroller;
- Using a specialized microcontroller, equipped with an A/D converter able to convert input voltages as low as µV and, thus, being extremely useful in direct coupling and compensating applications of thermocouples.

For our application, the use of the Texas Instruments specialized microcontroller MSC1210 conducted us to the second approach.

We have to mention from the beginning that we preferred to control the process using PID algorithms, considering their high efficiency proven in low noise corrupted and high time constants process control applications.

2. HARDWARE RESOURCES

2.1 The MSC1210 Development System

The development system used to implement the hardware core is organized around a MSC 1210Y5 microcontroller (Texas Instruments, (2002)), which is compatible with the 8051 family. The additional peripherals integrate into its structure and the microcontroller's facilities make possible to implement intelligent control systems dedicated for applications requiring high precision measurements. Fig. 2 shows the schematic diagram of the development system. The microcontroller's block diagram indicates its performance:

- MSC1210Y5 microcontroller;
- 8 analog input channels which can be configured as single-ended / differential ones, the A/D conversion being performed on 24 bits;
- 1 analog output channel, the D/A conversion being performed on 16 bits;
- 2 USART channels;
- 128K external memory RAM;
- 4 digital input/output 8 bits ports;
- speaker ;
- specialized module for generating sinusoidal, rectangular or triangle signal waveforms;

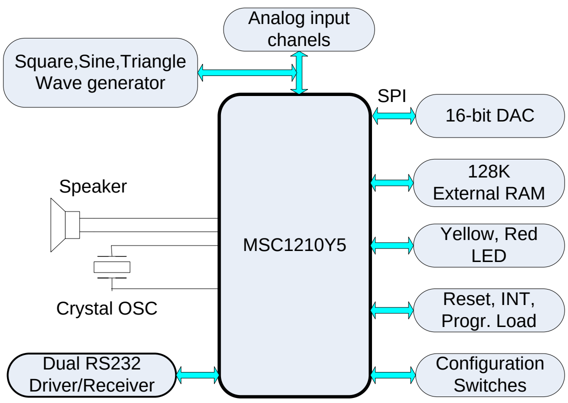

Fig. 2. Schematic diagram of the MSC1210EVM

MSC1210Y5 (fig. 3) is a fully integrated mixed signal devices family, including the following resources:

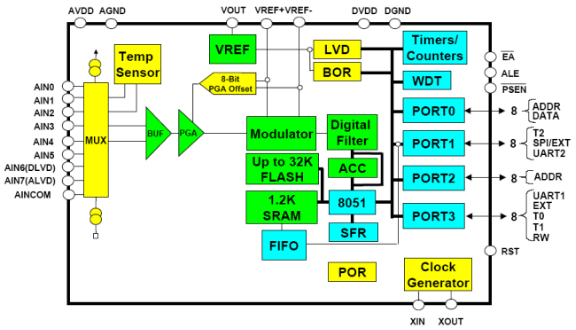

Fig. 3. Block diagram of MSC1210Y5 microcontroller

- 8 bits 8051 compatible processor;
- 8 channels analog multiplexor;
- 24 bits A/D converter;
- four 8 bits input/output ports;
- one watchdog timer (WDT)
- low supply voltage detection (LVD);
- ambient temperature detection;
- one 16 bits digital PWM output;
- three 16 bits timers/counters;
- 32K FLASH memory;
- 1.2K static RAM memory;
- Power On Reset;
- Brown Out Reset;
- interruption or short-circuit cable detection (Burnout);

The microcontroller includes a specialized module dedicated for ambient temperature measurement. This is performed by direct biasing of two diodes and measuring, in a differential manner, the voltage furnished by the sensors using the A/D converter. The diodes are biased using two current sources, providing biasing currents in a ratio of 1:80.

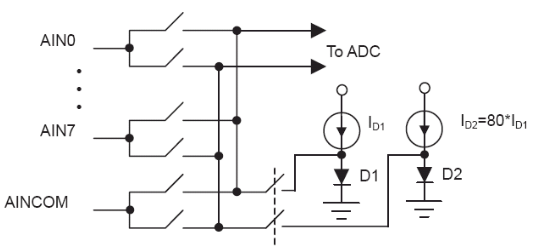

Fig. 4. Ambient temperature detection module

The differential voltage of the diodes provides the input of the A/D converter. It can be shown (Texas Instruments, (2003)) the dependence of this voltage versus temperature, using (1). The temperature is expressed in Kelvin, but it can be converted to any other measurement units.

$$\begin{aligned} U_{Temp} &= U_{D1} - U_{D2} = \\ &= \frac{nkT}{q}\left[\ln\left(\frac{I_{D2}}{I_s}\right) - \ln\left(\frac{I_{D1}}{I_s}\right)\right] = \\ &= \frac{nkT}{q}\ln\left(\frac{I_{D2}}{I_{D1}}\right) = \alpha T \end{aligned} \tag{1}$$

Experimental results, made by the developer of the microcontroller, have shown some deviations from the ideal expression, shown in (1). There errors are determined by the following parameters:

- the diode emission coefficient, n, is a function of the direct current;
- exact match of the diodes D_1 and D_2 is not possible; the saturation currents (I_s) of the diodes are not identical;
- the diodes current ratio is temperature dependent; when the differential voltage of the two diodes is computed using (1), the result is represented by a polynomial expression who's degree is grater by one ($U_{Temp}= aT^2+bT+c$);
- the currents ration for the two diodes pair is not the same for each microcontroller; thus we cannot use one singe alpha value for all circuits;
- the coefficients are calibrated using a specific, useful temperature domain, extrapolations conducting to errors. If T = 0K, the differential voltage is not equal to 0.

Texas Instruments, as the designer of the microcontroller, provides information about maximal errors which can be obtained using the polynomial approximation of the voltage versus temperature characteristic (linear curve fitting (2) or polynomial curve fitting). The temperature is expressed in degrees Celsius.

$$\begin{aligned} U_{Temp} &= \frac{nk\ln(80)}{q}(T_C + 273.15) = \\ &= mT_C + c \end{aligned} \tag{2}$$

Table 2. The estimated errors of the ambient temperature sensor

	Slope Coefficient m (μV/°C)	Intercept Coefficient c (mV)	Curve Fitting Accuracy (°C)	System Accuracy (°C)
Ideal Diodes	377.6	103.1	-	-
Linear Curve Fitted	386.7	104.98	+0.44/ −0.30	+0.49/ −0.35
Polynomial Curve Fitted	$U_{Temp} = 6.3595\text{x}10^{-5}T_C^2 + 0.3842T_C+104.90$		+0.045/ −0.048	+0.095/ −0.098

2.2 The Power Module

The power module which was designed for this application (fig. 5) performs optical insulation of the high power section and the low power section. This insulation is accomplished for both command and control signals.

Another objective of the design process of the power module was to reduce the costs to as low as possible, without affecting performances.

The control of the power signal is accomplished using a triac (Q_2) of 400Vac/40A, having specialized protection against dI/dt (the group consisting of R_4, C_1). Its control is realized in the first and the third quadrants using an opto-triac (MOC3020) who's output being also protected against dI/dt by the components group R_1, R_2, C_1.

The control signal furnished by the microcontroller is being adapted from +3V to +5V using open collector drivers (ULN2003). In order to prevent the situations of controlling large inductive loads, a PWM compatible signal was provided.

The power module transmits an interrupt to the microcontroller to signalize the zero-crossing of the output voltage. As a supplementary precaution measure the control signal is conditioned by the interrupt signal.

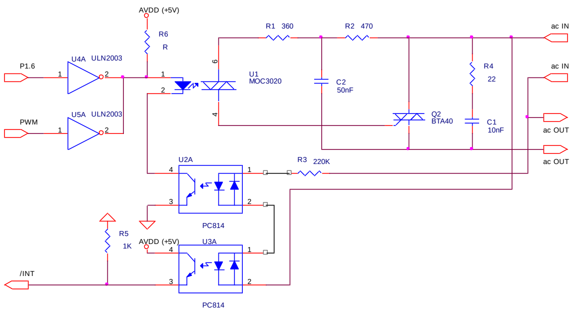

Fig. 5. Electrical schematics of the power module

2.3 Temperature Measuring Using Thermocouples

A primary advantage of thermocouples consists in the easiness of building them. Additional, they work well for a large domain of temperatures. The response of a thermocouple versus temperature have some disadvantages: the major one consists in the fact that these responses are non-linear. NIST (National Institute of Standards and Technology) has analyzed the behavior of thermocouples and elaborated a specialized standard. The NIST standard approximates the behavior of the thermocouples for different temperature ranges. Table 3 shows the temperature ranges and the appropriate approximation coefficients for type B thermocouples (NIST ITS-90 Thermocouple Database).

By connecting a thermocouple to a specific measurement equipment, due to wiring and connections, which are generally made using different materials, as Cu, some parasites thermocouples appear.

The appropriate voltage corresponding to the measured temperature represents a sum of the A/D voltage input and the equivalent voltage of the thermocouple for the measuring connection temperature.

This compensation process requires some conversion polynomial expressions: the direct polynomial for voltage to temperature conversion and the inverse polynomial for temperature to voltage conversion. Tables 3 and 4 show the direct and the inverse polynomials for type B thermocouples.

In order to accomplish parasite thermocouple compensation, in our control system the coupling temperature was determined using the temperature sensor of the MSC1210Y5 microcontroller (Texas Instruments, (2005)), the compensation expression being given by (3):

$$T^{o}C = P_2\left[E_{T_C} + P_1(T_{amb})\right] \quad (3)$$

The MSC121x microcontroller family integrates an ambient temperature sensor, within -40°C - +85°C temperature interval, characterized by high resolution and stability (the measurement accuracy is ±0.1%°C and the resolution is 0.01°C).

The equations describing the direct and the reverse polynomials are described in (4):

$$\begin{aligned} E &= P_1(T) = \sum_{i=1}^{n} c_i T^i \\ T &= P_2(E) = \sum_{i=1}^{n} d_i E^i \end{aligned} \quad (4)$$

where E is the thermoelectric potential, in mV, T is the temperature, in °C, and c_i, d_i are the coefficients of the direct and reverse functions, determined at 0°C.

Table 3. Type B Thermocouples direct polynomial approximation coefficients

	0°C to 630.615°C	630.615°C to 1820°C
c_0	$0.000000000000\text{x}10^{0}$	$-0.389381686210\text{x}10^{1}$
c_1	$-0.246508183460\text{x}10^{-3}$	$0.285717474700\text{x}10^{-1}$
c_2	$0.590404211710\text{x}10^{-5}$	$-0.848851047850\text{x}10^{-4}$
c_3	$-0.132579316360\text{x}10^{-8}$	$0.157852801640\text{x}10^{-6}$
c_4	$0.156682919010\text{x}10^{-11}$	$-0.168353448640\text{x}10^{-9}$
c_5	$-0.16944529240\text{x}10^{-14}$	$0.111097940130\text{x}10^{-12}$
c_6	$0.629903470940\text{x}10^{-18}$	$-0.445154310330\text{x}10^{-16}$
c_7		$0.989756408210\text{x}10^{-20}$
c_8		$-0.937913302890\text{x}10^{-24}$

Table 4. Type B Thermocouples reverse polynomial approximation coefficients

	250°C to 700°C		700°C to 1820°C	
Voltage range	0.291mV to 2.431mV		2.431mV to 13.820mV	
d_0	9.8423321	$x10^1$	2.1315071	$x10^2$
d_1	6.9971500	$x10^2$	2.8510504	$x10^2$
d_2	-8.4765304	$x10^2$	-5.2742887	$x10^1$
d_3	1.0052644	$x10^3$	9.9160804	$x10^0$
d_4	-8.3345952	$x10^2$	-1.2965303	$x10^0$
d_5	4.5508542	$x10^2$	1.1195870	$x10^{-1}$
d_6	-1.5523037	$x10^2$	-6.0625199	$x10^{-3}$
d_7	2.9886750	$x10^1$	1.8661696	$x10^{-4}$
d_8	-2.4742860	$x10^0$	-2.4878585	$x10^{-6}$
Error range	-0.02 °C to 0.03 °C		-0.01 °C to 0.02 °C	

The intelligent control system was equipped with a type B thermocouple. Despite that the NIST Standard doesn't offer a polynomial approximation expression for 0^oC to 250^oC temperature range, an interpolation polynomial approximation has been obtained according to the values provided by the thermocouple manufacturer. An interpolation application has been developed using MATLAB.

```
%the conversion polynomial from mV in degrees Celsius for B type thermocouples (Pt18)
%temperature range 40-250 degrees Celsius
T=40:10:250;
V=[0.000 0.002 0.006 0.011 0.017 0.025 0.033 0.043 0.053 0.065 0.078 0.092 0.107 0.123 0.140 0.159 0.178 0.199 0.220 0.243 0.266 0.291];
format long G
pol=polyfit(V,T,8)

Polynomial degree 8
pol =
  1.0e+008 *
  Columns 1 through 6
-5.61636683825532         6.86785323587866
-3.47433170039631         0.94108747033290
-0.14783038502476         0.01371635336516
  Columns 7 through 9
-0.00075551168067         0.00003192798648
 0.00000042149810
```

3. THE PID CONTROL ALGORITHM

Slow processes can be characterized by approximated models, having large time constants (greater than 10 seconds), and, most often, having dead times. In order to choose the appropriate type of regulator, the designer use a series of verified by practice criteria, taking into account the specificity of the process and the desired performances. The presence of the dead time into a technological process needs some precautions in choosing the regulator type, being recommended either PI / PID linear regulators, or bi-positional / tri-positional nonlinear regulators (Dumitrache, I., *et al.* (1993)).

For temperature control in which the ratio τ/T_p is large, it is recommended to use PID control in order to minimize the stationary error and to ensure a high speed response. The process model can be characterized by the transfer function, given in (5) (Dumitrache, I., (2005)).

$$H(s) = \frac{K_p e^{-\tau s}}{T_p s + 1} \tag{5}$$

The implemented PID control is based on the continuous without influence law, given in (6).

$$u = K_R\left(\varepsilon + \frac{1}{T_i}\int \varepsilon dt + T_d\frac{d\varepsilon}{dt}\right) \tag{6}$$

Using the discretization rectangle method, this expression can be expressed by (7), where T is the sampling period.

$$u_k = K_R\left(\varepsilon_k + \frac{T}{T_i}\sum_{i=1}^{k}\varepsilon_i + T_d\frac{\varepsilon_k - \varepsilon_{k-1}}{T}\right) \tag{7}$$

In order to obtain a recursive algorithm, we compute the command for the k-1 step (8):

$$\begin{aligned} u_{k-1} = K_R\left(\varepsilon_{k-1} + \frac{T}{T_i}\sum_{i=1}^{k-1}\varepsilon_i\right) + \\ +K_R\left(T_d\frac{\varepsilon_{k-1} - 2\varepsilon_{k-2}}{T}\right) \end{aligned} \tag{8}$$

Combining by subtraction the last two expressions, we can obtain the command expression (9).

$$\begin{aligned} u_{k-1} = K_R\left(\varepsilon_k - \varepsilon_{k-1} + \frac{T}{T_i}\varepsilon_k\right) + \\ +K_R\left(T_d\frac{\varepsilon_k - 2\varepsilon_{k-1} + \varepsilon_{k-2}}{T}\right) \end{aligned} \tag{9}$$

The integral component was limited so it doesn't determine the command saturation.

3.1 Methods for Regulator Accord

The accord parameters of a numerical PID algorithm can be optimized using one of the following methods:

- using a model of the process we can obtain optimal parameters using an appropriate performance criteria;
- knowing the process model we can determine the optimal parameters using an allocation method;
- using accord rules based on characteristics raised using the indicial response or the oscillations determined for the stability limits.

Experimental accord criteria of the regulator using indicial response results. The difficulties of precise identification of slow processes, their non-linear behavior, and the stochastic character of some disturbances make that analytical methods for accord PID numerical regulators to be limited. In most cases, after an accord procedure based on a specified criteria, it is necessary to verify regulator performances and to readjust the accord parameters.

The used accord method is based on experimental determination of the following parameters τ, T_p, K_p, using a step signal excitation.

The procedure consists of:

- appling a step signal waveform, from u_0 la u_{st} (representing a percent of 10%-20% of the whole command magnitude), at the input of the open-loop system, functioning into a stationary regime described by input-output signals (u_0, y_0), at a specified moment of time (t_0);
- determining the new stationary regime values of the process;
- computing the parameters of the mathematical model (5), using (10):

$$K_F = \frac{y_{st} - y_0}{u_{st} - u_0};\ \tau = t_2 - t_1;\ T_F = t_3 - t_2 \quad (10)$$

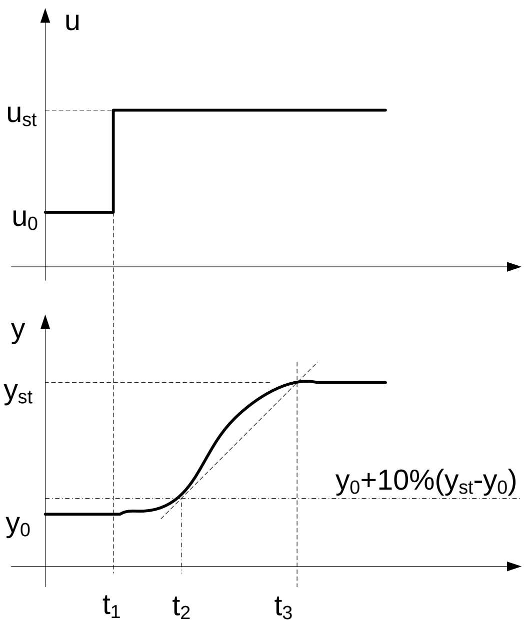

Fig. 6. Typical step response of the process

Using these values, obtained on experimental basis, we can determine the optimal accord parameters of the PID regulator. The Ziegler-Nichols expressions for the PID regulator are (11):

$$K_{R\,opt} = \frac{1.2T_F}{K_F\tau};\ T_{i\,opt} = 2\tau;\ T_{d\,opt} = 0.5\tau \quad (11)$$

The sampling Period Optimization. The accord parameters optimization of a PID numerical regulator implies choosing optimally the sampling period. Within the case of according the regulator on the base of results obtained using the indicial response, we recommend the values described by (12):

$$\begin{aligned} T &= (1.5 \ldots 0.35)\tau \quad \text{if } 0.1 \le \tau/T_F \le 1 \\ T &= (0.35 \ldots 0.22)\tau \quad \text{if } 1 \le \tau/T_F \le 10 \end{aligned} \quad (12)$$

4. THE STRUCTURE OF THE APPLICATION

4.1 The structure of the embedded application

The program implemented into the microcontroller was written in C-Keil µVision. The sampling period was chosen 3 seconds. The block diagram of the application is shown in fig. 7.

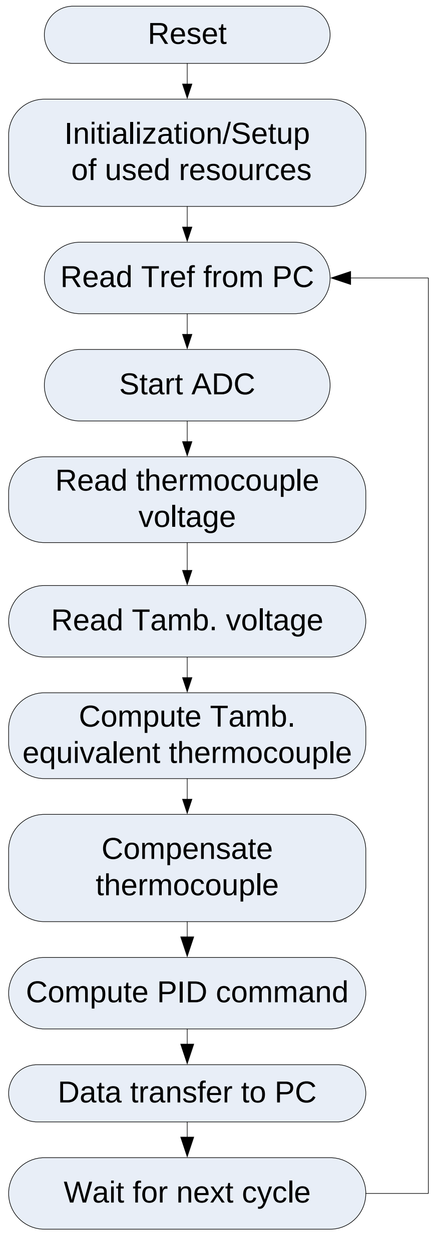

Fig. 7. Schematic diagram of the embedded application

4.2 User Interface Implementation

LabVIEW is a graphical programming language used for easy developing of applications using pictograms. Text-based programming languages use specific instructions to determine the program flow. In LabVIEW uses data flows implemented by an appropriate graphical representation.

Its name derives from its developer, National Instruments, who named the applications as virtual instruments (VI).

LabVIEW, from its previous versions, has as goal to realize a substitute for different electronic instruments and apparatus, using a personal computer.

From the beginning, LabVIEW cloned the front panels of some major electronic instruments and their modes of operation. LabVIEW signifies the abbreviation from the complete English name: Laboratory Virtual Instrument Engineering Workbench.

The user interface (fig. 8) was implemented using the LabVIEW programming language. This interface integrates the following functions (fig. 9):

- Creating a serial object and the configuration of its parameters;
- Configuring the ending character;
- XON/XOFF protocol implementation;
- Sending data to the serial object routine implementation;
- Receiving data from the serial object routine implementation;
- The reference temperature programming;
- Sent / received data saving, using different types of files (.xls , .txt);
- Displaying the programmed and measured temperatures, using charts (for 10 minutes display) and graphs (for the last minute).

5. CONCLUSIONS

This paper is focused on interdisciplinary, systemic approach of designing a closed-loop temperature control system. This is a slow process, involving some major difficulties in precise measuring, identification and process control. Developed using an intelligent hardware, a distributed (oriented on the hardware-layer and on a personal computer layer) software application is performing the process identification, adjusting the control parameters and the process control in an optimal manner. The system allows viewing the process evolution and keeping an extended history of its evolution. The implementation minimizes measuring errors, performs optimal control, and thus assuring high performances and low costs.

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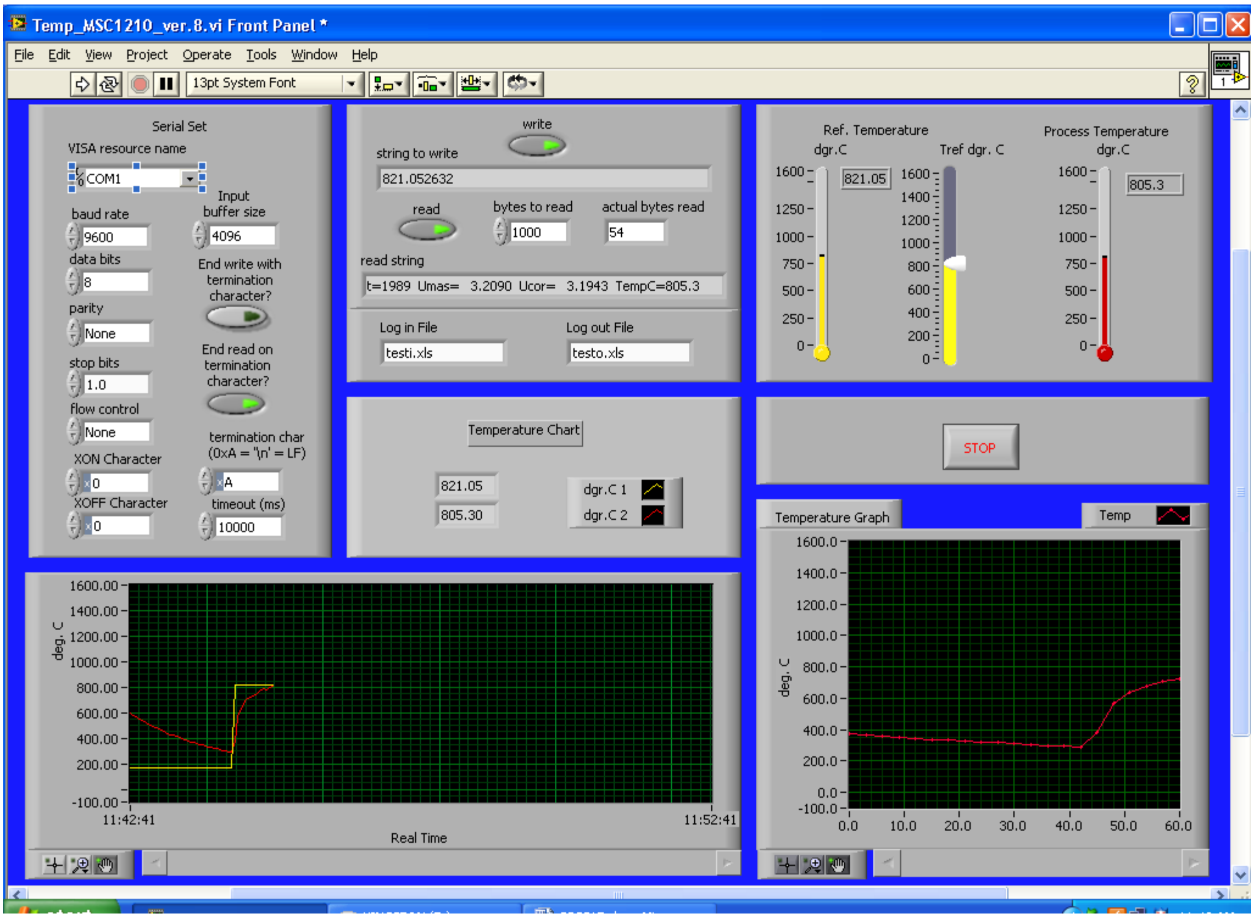

Fig. 8. The front panel of the user interface.

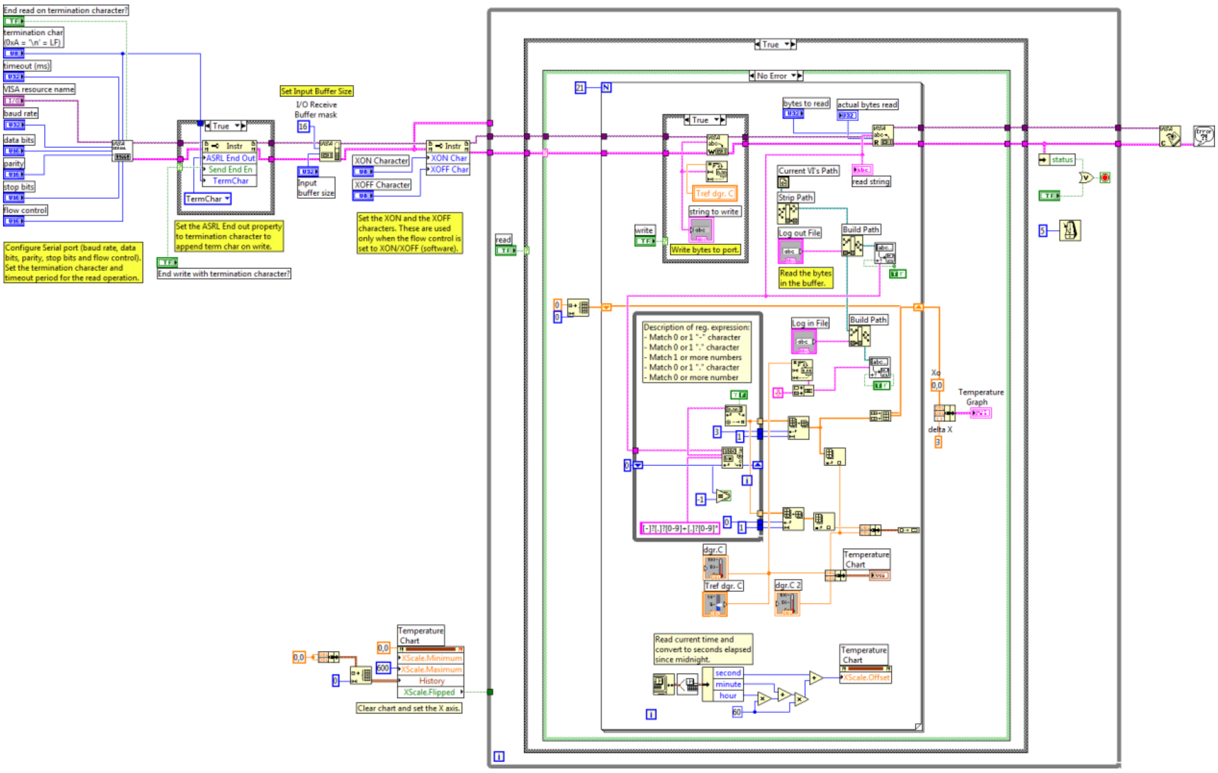
Fig. 9. The LabVIEW block diagram of the user interface